Technical Article

Using Helicopter Electromagnetic Surveys to Identify Environmental Problems at Coal Mines

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Abstract. Helicopter-mounted electromagnetic (HEM) surveys have been used to delimit conductive mine pools and groundwater features at various areas in the eastern United States that contain abandoned surface and underground coal mines. HEM was used to delineate the source areas and flow paths for acidic, metal-containing groundwater. This will aid remediation efforts. A recent HEM survey of Kettle Creek Watershed, Clinton County, Pennsylvania, using a 6-frequency electromagnetic data acquisition system, is presented. The survey accurately located conductive pools within underground mines, acid-generating mine spoil at surface mines, and areas of groundwater recharge and discharge.

Key words: Acid mine drainage; airborne electromagnetic survey; EM; helicopter

Introduction

Since 1999, the U.S Department of Energy's National Energy Technology Laboratory (NETL) has conducted helicopter electromagnetic (HEM) surveys of seven coal mining areas in West Virginia, Pennsylvania (Pa), Ohio, and Maryland (Figure 1). The purpose of these surveys was to determine if HEM surveys can provide hydrologic information that is useful for hazard identification and to aid mine water remediation efforts. Such information could include the location of:

- flooded mine workings
- abandoned mine discharges
- mine water recharge zones
- paths taken by water through abandoned mine workings.

In 2002, national attention was drawn to nine miners who were entrapped by water in the Quecreek Mine in south-central Pa. This accident resulted from mining operations that inadvertently encountered water ponded within an incorrectly mapped, abandoned mine. Although the miners were successfully rescued, this accident heightened national resolve to map inadequately documented mine workings, and has redoubled our efforts to use HEM for detecting mine pools. Generally, pools that develop in underground mines are more conductive than the strata above and below the mine, and therefore, offer high-contrast targets for electromagnetic survey methods. However, the mine pool together with the underclay (also conductive) is only about 2 to 4 m thick, and is overlain by 10 to 400 m of less conductive strata. The ability to detect mine pools diminishes with depth and with decreasing contrast between the conductivity of the mine pool and the conductivity of the overburden. The response of HEM systems to conductive mine pools can be simulated by forward models that are generated using available geologic information. Models of HEM system response constructed by Fugro Airborne Surveys suggest that frequency domain HEM can detect a 2-m thick mine pool with a conductivity of 500 mS beneath as much as 50 m of overburden with an average conductivity of 20 mS (Figure 2). The models also indicate that time domain electromagnetic surveys from a fixed-wing aircraft may be able to detect the same mine pool beneath up to 100 m of overburden (Smith 2002).

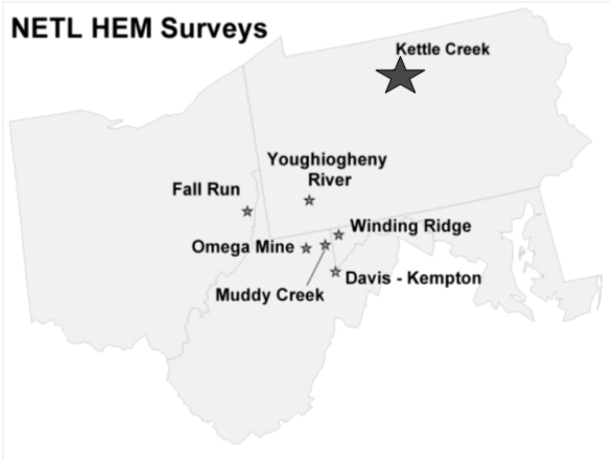

Figure 1. HEM surveys of coal mining areas in Pennsylvania, West Virginia, Ohio, and Maryland

The survey discussed in this paper is the most recent HEM survey conducted by NETL and is located in the Kettle Creek Watershed, in north-central Pa (Figure 1). This survey benefited from the experience gained from six previous surveys and from the continuous improvement in HEM technology that has occurred since the first survey was flown in 1999.

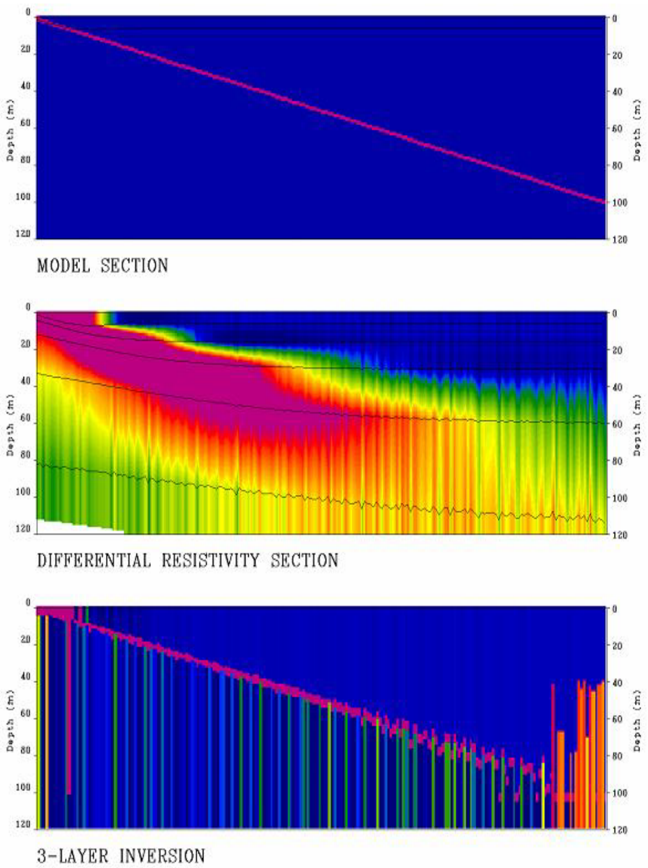

Figure 2. Modeled response of HEM system to a 2-m thick mine pool with 500 mS/m conductivity beneath overburden with average conductivity of 20 mS/m (from Hodges 2002)

Site Description

Kettle Creek Watershed encompasses approximately 245 mi^2 (633 km^2) of the Mountainous High Plateau Section of the Allegheny Plateau Physiographic Province. Elevations range from 229 m in the stream valleys to over 488 m on the highest ridges. The "depth of dissection [is] greater than 244 m generally" (Briggs 1999); in this watershed the relief can be as much as 274 m. The ridges in this area have "relatively broad tops [and] are at elevations similar to those of adjacent plateau areas" (Briggs 1999) while the valleys are very deep and narrow.

The ridges of the study area are underlain by the Pennsylvanian Age Allegheny Formation, a repeating succession of coal, limestone, and clastics, ranging from claystone to coarse sandstone (Edmunds et al. 1999). However, within the survey area, the series contains little if any limestone and is a cycle of sandstone, shale, coal, and fireclay (underclay) (Sisler 1924). Although the Allegheny formation sometimes contains as many as six coalbeds that are interspersed with thick sandstone and shale units; coal has been mined only from the Middle and Lower Kittanning Seams within the Kettle Creek Watershed. Both seams were surface mined from the early 1930's to the 1970's, yet most production was from the Middle Kittanning Seam because of shallow overburden. Underground workings were developed in the Lower Kittanning Seam in the late 1860's and continued until the 1950's. Following mining, many underground workings filled with water and are now discharging acid mine drainage (AMD) with pH ranging from 1.98 to 4.5.

The survey area west of Kettle Creek contains about 16 underground mines. Mine maps do not exist for the eastern survey area although there is surface evidence of underground mines (Klimkos 2000).One objective of this survey was to provide the location of deep mined areas in the eastern watershed.

The observed subsidence (sinkholes) indicate that the underground mines have largely caved in (collapsed), due presumably to the relatively shallow overburden and a lack of engineered roof control. It was viewed as likely that the underground mines, though above drainage, would contain numerous small impoundments or pools within the mine workings, although the voids would only be partially inundated.

Survey Description

Fugro Airborne Surveys performed the HEM survey of Kettle Creek Watershed in July and August 2002 using the RESOLVE electromagnetic data acquisition system. This system consists of five coplanar transmitter/receiver coil pairs operating at frequencies of 393 Hz, 1.53 kHz, 6.20 kHz, 28.2 kHz, and 107 kHz and one coaxial transmitter/receiver coil pair that operated at a frequency of 3.23 kHz. Separation for the five coplanar coil pairs was 7.9 m; separation for the coaxial coils was 9 m. A complete description of the RESOLVE HEM system is available at http://www.fugroairborne.com/Services/airborne/EM/resolve/index.shtml. Moreover, a general description of airborne HEM surveying is provided in this issue (Hammack et al. 2003).

The Kettle Creek survey was flown in an azimuthal direction of 70° with a line spacing of 50 m using a helicopter (Ecureuil AS350-B3) and pilot provided by Questral Helicopters, Inc. Average sensor height was 33.5 m and terrain compliance throughout the survey was excellent, especially when the ruggedness of the terrain is considered.

Data Processing

Conductivity/depth images (CDIs) along flight lines were constructed with EM Flow software (Encom 2001a) using navigational data and leveled in-phase and quadrature data from the HEM survey. Conductivity/depth images were converted into Geosoft database files and imported into Profile Analyst (Encom 2001b), where the CDIs were compared with available maps showing mine workings, inferred mine pools, and overburden thickness. Driller's logs from nearby boreholes were compared to the CDIs to determine the accuracy of the EM data and processing.

Results and Discussion

Location of mine pools

Airborne HEM surveys identified approximately 12 mine pools in shallow (<50-m deep) underground coal mines within the Kettle Creek Watershed. Figure 3 is a map of one identified mine pool inset with a CDI for a flight line that crosses over the mine. In the western part of the survey where mine maps are available, the location of mine pools coincides with the location of known mine workings (Figure 3). The discontinuous red zones shown in the figure could indicate large impoundments, or water that is more highly contaminated (more conductive) due to the oxidation of pyritic material. However, the HEM survey also has identified what are believed to be flooded workings east of Kettle Creek where no mine maps exist (Figure 4).

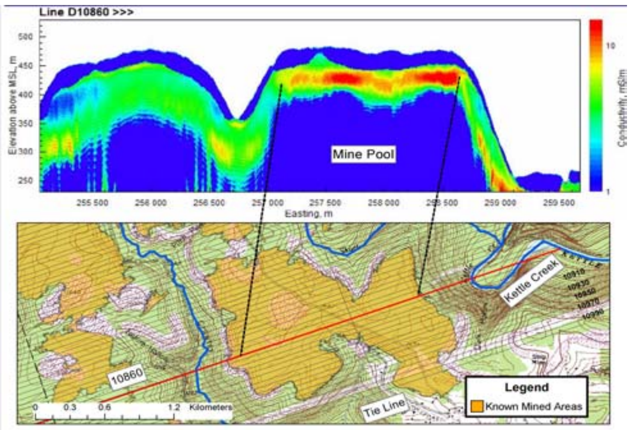

Figure 3. Inferred mine pools (red and yellow zones) correspond to mapped underground coal mine workings

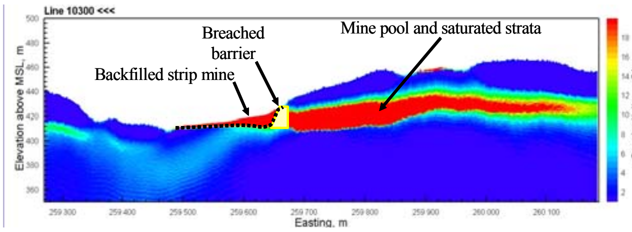

Figure 4. Conductive pool in previously unmapped mine workings

Sams and Veloski (2003) found that the conductivity of mine pool outflows in the Kettle Creek survey area ranged from 26 to 385 mS/m but averaged 160 mS/m. The actual conductivity of the mine pools (160 mS/m) was about one third of the value input for mine pool conductivity (500 mS/m) in forward models (Figure 2). Likewise, the apparent conductivity of the overburden (< 6 mS/m) was about one third of the model conductivity (20 mS/m). Therefore, the conductivity contrast between the mine pool and the overburden was expected to be similar to that of the model. Forward models suggested that HEM could identify a 2-m thick mine pool of 500 mS/m conductivity beneath as much as 50 m of 20 mS/m overburden. Mine pools less than 2-m deep with conductivities less than 300 mS/m were identified beneath as much as 50 m of overburden by HEM in this survey. This suggests that the results of the forward models were conservative.

The capability of delineating mine pools is especially important in areas where mining is taking place adjacent to abandoned mines with incomplete or missing mine maps. Having an accurate location of mine pools allows current mines to maintain safe barriers between active and abandoned workings, and prevent the unexpected, often catastrophic flooding of active mines. Furthermore, knowing the location of contaminated mine pools can facilitate in situ treatment, which can sometimes be more cost effective than treating water at discharge points.

Location of seeps

The airborne HEM survey of Kettle Creek depicted the groundwater table as a zone of anomalous conductivity that is usually 0-20 m below the surface. As expected, areas where the conductive zones intersected the surface (Figure 5) were often found to correspond with the location of springs and seeps associated with mine discharges previously identified using night-time thermal infrared (TIR) imagery (Sams and Veloski 2003). Although the TIR imagery was acquired during leaf-off conditions, areas of non-deciduous trees and shrubs obscured a number of groundwater discharge points. An expensive, time-consuming search by foot could locate groundwater discharges that are hidden beneath non-deciduous vegetation, but with HEM, the time and cost of such a search could be reduced by limiting the search to areas where near-surface conductive anomalies coincide with non-deciduous cover.

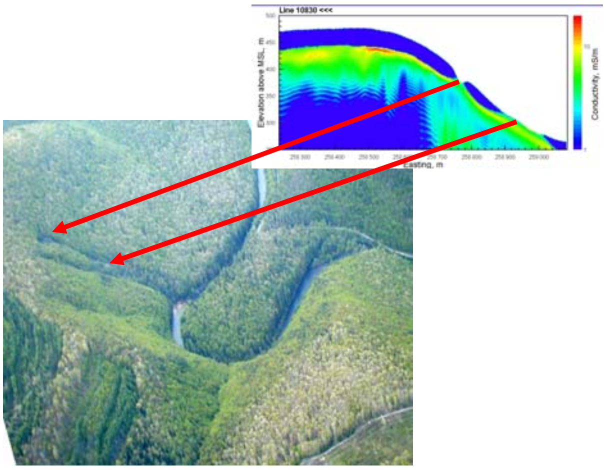

Figure 5. Springs and seeps are commonly located where the conductive zone (water table) is near the surface

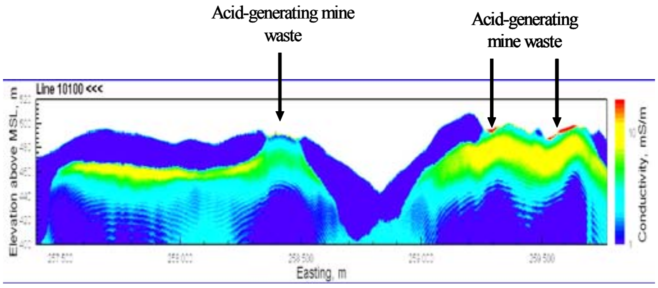

Figure 6. Acid-generating mine spoils are depicted as highly conductive areas near the surface

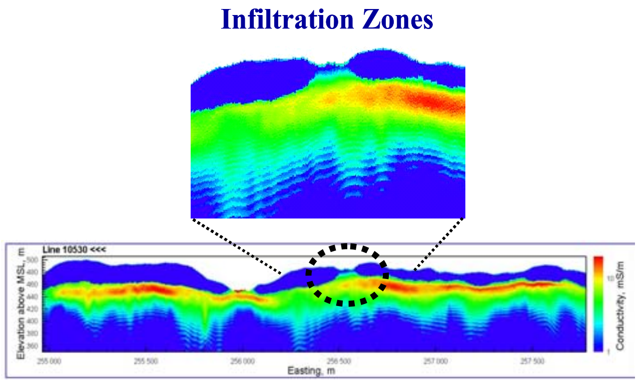

Figure 7. Infiltration zones are depicted as vertical conductive zones between surface mined areas and the horizontal conductive zone (water table)

Location of acid-generating mine spoils

Figure 6 is a CDI that depicts several thin, conductive anomalies on the surface. These surface conductors always occur within areas that have been disturbed by surface mining activities. However, not all surface mined areas are anomalously conductive. We believe that the near-surface conductors indicate the location of mine spoil with high concentrations of weathering pyritic material. Reclamation of areas disturbed by surface mining was previously attempted using rough grading and planting of conifers. However, in areas where infiltration is occurring, the reclamation was not successful. If this can be verified by subsequent ground-based surveys, then airborne FDEM may be a technique to scan large surface mining regions and quickly target acid-generating material for remediation.

Location of infiltration zones

The airborne FDEM survey identified numerous areas where conductive water from surface mines appear to be infiltrating into the underlying mine works. Figure 7 is a CDI where the infiltrating water is shown as a conductive green-blue band that extends vertically between a contour surface mine and a pool of conductive water (darker green, yellow, and red) within an underground mine. The identification of infiltration zones aids remediation efforts by targeting surface mined areas for regrading or capping to prevent the infiltration of meteoric waters and recharge of the perpetually draining mine pools.

Conclusions

A HEM survey of the Kettle Creek Watershed, a rugged area with abandoned surface and underground coal mines, was conducted to locate underground mine pools, acid-generating mine spoil, groundwater recharge and discharge areas, and aquifers contaminated by mining activities. The survey met all objectives. Site conditions and survey execution that contributed to the success included:

- the underground mine pools in this area were less than 50-m deep, and beneath a less conductive overburden than other coal mining areas flown by NETL,
- the pilot was experienced with HEM surveys and maintained excellent terrain conformity despite the rugged topography,
- minimal interference from power lines or other cultural features, and
- better response, calibration, and noise rejection by a new digital HEM system.

Information obtained from the Kettle Creek Watershed survey included: 1) the location of underground mine pools, 2) the location of mine drainage seeps, 3) the location of acid-generating spoil, and 4) the location of groundwater recharge zones. This information is now being used by watershed management groups to formulate cost-effective remediation plans.

Acknowledgements

This project was funded by a Growing Greener Grant awarded to Trout Unlimited. The authors thank Neil Wolfe and Amy Gottesfeld of Trout Unlimited for field and technical support.

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